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# Measurement of the production rates of $\eta$ and $\eta'$ in hadronic Z decays

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The decays $\eta \to \gamma\gamma$ and $\eta' \to \eta\pi^+\pi^-$ have been observed in hadronic decays of the Z produced at LEP. The fragmentation functions of both the $\eta$ and $\eta'$ have been measured. The measured multiplicities for $x > 0.1$ are $0.298 \pm 0.023 \pm 0.021$ and $0.068 \pm 0.018 \pm 0.016$ for $\eta$ and $\eta'$ respectively. While the fragmentation function for the $\eta$ is fairly well described by the JETSET Monte Carlo, it is found that the production rate of the $\eta'$ is a factor of four less than the corresponding prediction.

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## 1. Introduction

The $\eta$ and $\eta'$ have been seen in many high energy $e^+e^-$ experiments [1–4], however only the MARK II Collaboration [1] has attempted to measure the inclusive production rate of the $\eta'$. In this letter, measurements of the production rates of both $\eta$ and $\eta'$ using the ALEPH detector at LEP are reported and comparison is made with the predictions of JETSET and HERWIG .

While the relative production rate of the $\eta'$ is quite low (less than one $\eta'$ per hadronic decay of the Z), it can produce a significant effect. This has been found to be the case in studies of the Bose–Einstein effect [5,6] where there are large corrections in the region of interference at low invariant mass arising from the products of long-lived ($c\tau \gg 1$ fm) particles. The $\eta'$ ($c\tau = 950$ fm) gives rise to an average of 1.8 charged pions per decay, which tend to have low invariant mass because of limited phase-space. Therefore the $\eta'$ potentially represents a major part of the correction to the measurement of the strength of the Bose–Einstein effect. It has been pointed out [7] that if the production rate of $\eta'$ in the JETSET Monte Carlo is substantially larger than that which occurs in actual $e^+e^-$ annihilations, the corrections for the Bose–Einstein studies will have been overestimated. This may explain why some of the measurements of the strength of the effect exceed the maximum values allowed by JETSET. The $\eta'$ production rate is also of interest since it affects particle multiplicities and energy sharing and provides information on the transition from partons to hadrons.

For the comparisons with Monte Carlo, the JETSET 7.3 (parton shower) program [8] has been used with default values for the $s/u$ and pseudoscalar/vector ratios. Parameters related to global event shape and particle multiplicity were tuned to reproduce ALEPH data [9]. The HERWIG 5.4 program [10] has been used with default parameters.

## 2. The ALEPH detector and hadronic event selection

Details of the ALEPH detector and the trigger are described elsewhere [11]. Here the detector components relevant to this analysis are reviewed. The momenta of charged particles are measured in two central tracking chambers. The inner tracking chamber (ITC) is a conventional drift chamber which provides up to 8 coordinates per track. The outer chamber, a large time projection chamber (TPC) of radius 1.8 m, yields up to 21 additional space points per track. Both chambers are located inside a superconducting solenoid and give a momentum resolution of $\sigma_p/p = 0.0008p \oplus 0.003$ (with $p$ in GeV/$c$). Beyond the TPC, but still inside the solenoid is the electromagnetic calorimeter (ECAL). This is a lead-proportional tube calorimeter which has an energy resolution for electromagnetic showers of $\sigma_E/E = 0.017 \oplus 0.19/\sqrt{E}$ (with $E$ in GeV) and an angular resolution of $\sigma_\theta = 3.7/\sqrt{E}$ (with $\theta$ in mrad). It covers an angular range of $|\cos\theta| < 0.98$ and is finely segmented into projective towers, each subtending a solid angle of approximately 0.8° by 0.8°. These towers are read out in three longitudinal stacks corresponding to thicknesses of approximately 4, 9 and 9 radiation lengths. Beam tests have shown that for high energy electrons (above 10 GeV), the fraction of the electron energy contained in the four towers (in a two by two group) closest to and including the impact point is 85% in the barrel and 89% in the end-caps on average.

For this analysis, data collected with the ALEPH detector at a centre-of-mass energy of 91.2 GeV during the 1990 and 1991 running of LEP has been used. Hadronic decays of the Z were selected by demanding that reconstructed events contained at least five *good* charged tracks and that the energy carried by these tracks exceeded 10% of the centre-of-mass energy. For the purposes of event selection, a *good* track was defined as one which had at least 4 coordinates in the TPC, which originated from a cylindrical region of radius 2 cm and half-length 10 cm centred on the nominal interaction point and which had $|\cos\theta| < 0.95$. This yielded a sample of 356 000 hadronic Z decays.

The reconstruction and selection efficiency for the decays of the $\eta$ and the $\eta'$ have been determined from Monte Carlo simulated events. These were generated with JETSET, subjected to a detailed simulation of the ALEPH detector and selected with the same analysis procedure as used for the real data.

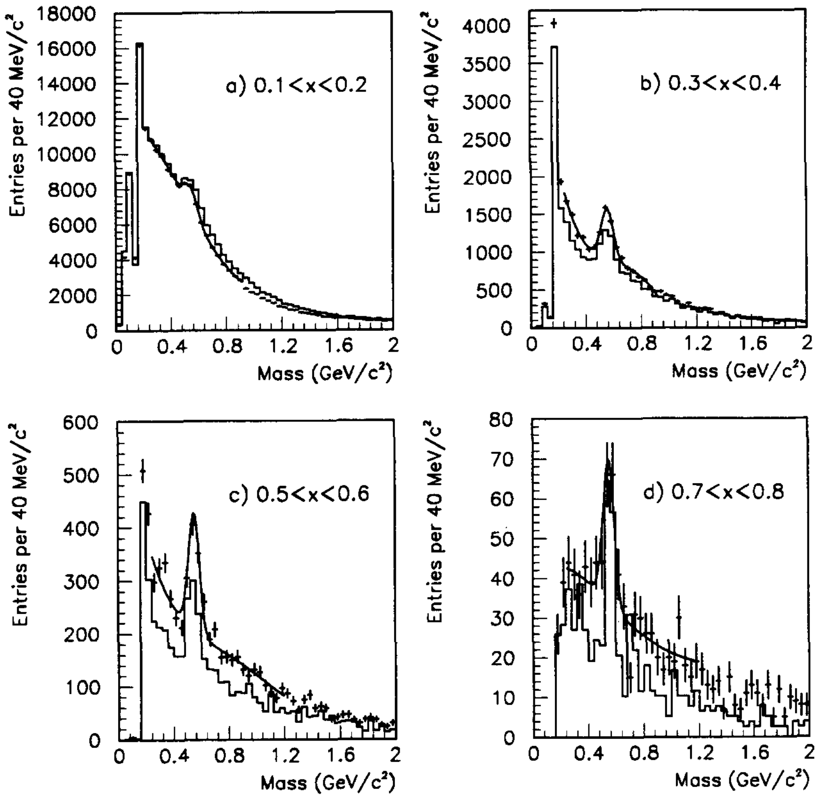


Fig. 1. $\gamma\gamma$ mass spectra for different values of $x = E(\gamma\gamma)/E_{\mathrm{beam}}$. ALEPH data are shown as points with error bars and corresponding fits. Fully simulated Monte Carlo data (using JETSET 7.3 and normalised to the ALEPH data) are shown as histograms.

### 3. Measurement of the production of the $\eta$

The $\eta$ is identified by its decay into two photons. Photons were reconstructed in the ECAL by looking for local maxima within clusters of towers containing energy deposits. A maximum tower was defined as one which contains more energy than any of the towers with which it shares an edge, and this tower was used as the starting point for the creation of a new subcluster. The remaining towers were assigned in order of decreasing energy, adding the energy of a tower to the same subcluster as its highest energy neighbour. Photon candidates were required to have subclusters extending in depth over at least two stacks in order to reject satellite clusters of hadronic showers. For complex clusters associated with charged tracks, it was required that the barycentre of any subcluster should be at least 2 cm from the extrapolation of each charged track for that subcluster to be considered a photon candidate. The energies of the candidate photons were required to be greater than 1 GeV.

Most of the background to the $\eta$ signal arises from combinations formed from photons originating from $\pi^0$ decays. For a given event, all $\gamma\gamma$ pairs were formed, and if a pair was within 25 MeV/$c^2$ of the $\pi^0$ mass (corresponding to about 1.5 $\sigma$) both photons were discarded. Finally the energies of all remaining photons were required to be greater than 2 GeV.

The mass distribution for all pairs formed from the selected sample of photons was obtained in several intervals of the fragmentation variable $x = E(\gamma\gamma)/E_{\mathrm{beam}}$. These intervals extend from $x = 0.1$

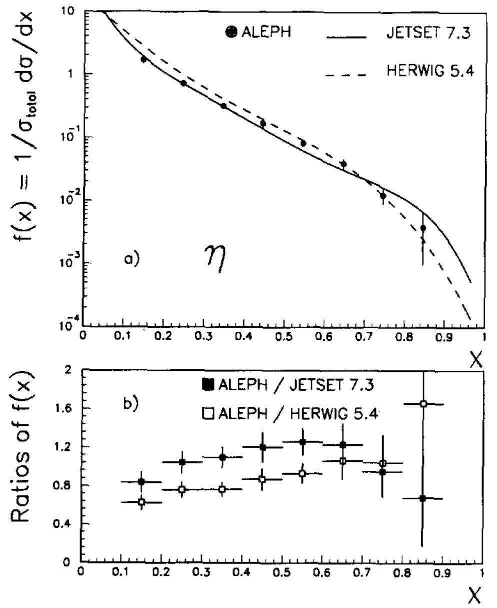


Fig. 2. (a) The corrected $\eta$ fragmentation function compared with the predictions from JETSET 7.3 and HERWIG 5.4. (b) The ratios of the fragmentation functions. All errors shown are statistical only.

to $x = 0.9$ in steps of $\Delta x = 0.1$. In each $x$ interval, the mass spectrum was fitted with a gaussian and a quartic polynomial for the background, and the fitted signal was normalised to the number of hadronic Z decays selected. For $x < 0.5$, the spectrum was fitted in the mass range 0.24 to 0.92 GeV/$c^2$. For $x > 0.5$, the range was extended to 1.20 GeV/$c^2$ to reduce the statistical error from the background. In this region, the mean of the gaussian was constrained to the $\eta$ mass and the resolution fixed at 40 MeV/$c^2$. The $\gamma\gamma$ mass distributions from the data and the simulated Monte Carlo, along with the fits corresponding to the data, are shown in fig. 1.

The efficiency was obtained as a function of $x$, and varies from about 16% at the lowest $x$ to about 46% for $x > 0.5$. The reduction at low $x$ is due to the 2 GeV threshold on the photon energy. To obtain the fragmentation function, defined by

$$f(x) = \frac{1}{\sigma_{\text{total}}} \frac{d\sigma}{dx},$$

and shown in fig. 2, the measurements are corrected for the efficiency losses and the 39% branching ratio

Table 1
The corrected $\eta$ fragmentation function. The errors shown are statistical only while the systematic error on each value (not shown) is about ±7%.

| $x$ range | $(1/\sigma_{\text{total}})\, d\sigma/dx$ |
|---|---|
| 0.1–0.2 | $1.68 \times 10^{0} \pm 0.22 \times 10^{0}$ |
| 0.2–0.3 | $6.80 \times 10^{-1} \pm 0.64 \times 10^{-1}$ |
| 0.3–0.4 | $3.27 \times 10^{-1} \pm 0.34 \times 10^{-1}$ |
| 0.4–0.5 | $1.68 \times 10^{-1} \pm 0.22 \times 10^{-1}$ |
| 0.5–0.6 | $8.13 \times 10^{-2} \pm 0.93 \times 10^{-2}$ |
| 0.6–0.7 | $3.87 \times 10^{-2} \pm 0.76 \times 10^{-2}$ |
| 0.7–0.8 | $1.24 \times 10^{-2} \pm 0.33 \times 10^{-2}$ |
| 0.8–0.9 | $3.80 \times 10^{-3} \pm 2.85 \times 10^{-3}$ |

for $\eta \to \gamma\gamma$. The fragmentation function is compared with the JETSET prediction and agrees over all the $x$ range to better than 40%, although the measured fragmentation is a little harder. The HERWIG prediction is good for $x > 0.4$, but gives too many $\eta$ particles at lower $x$ values. The values of the fragmentation function can be found in table 1.

The $\eta$ multiplicity is obtained by integrating the corrected fragmentation function. For $x > 0.1$, the data yield $0.298 \pm 0.023$ (stat) $\pm 0.021$ (syst) $\eta$ per Z decay, in good agreement with the JETSET prediction of 0.33, but significantly below the HERWIG prediction of 0.44.

The systematic error is derived from a detailed comparison between data and the simulation. Uncertainties have been estimated for single photons corresponding to (a) the use of the photon algorithm, (b) the variation of efficiency within different geometrical regions of the ECAL, (c) the effect of a 1% uncertainty in the calibration of the energy scale of the ECAL at the low energy threshold and (d) the description of the loss of photons by conversions. The combination of all of these uncertainties taken in quadrature leads to a systematic error of 2.5% per photon. The error on the reconstruction of an $\eta$ from two photons has been taken as twice this and is combined in quadrature with a 5% uncertainty estimated from varying the fitting procedure. This yields a total systematic uncertainty of 7% on the corrected fragmentation function and hence on the multiplicity.

For $x < 0.5$, where the bulk of the data lie, the background under the $\eta$ mass peak is correctly simulated to 20%, as can be seen in fig. 1. For $x > 0.5$, the

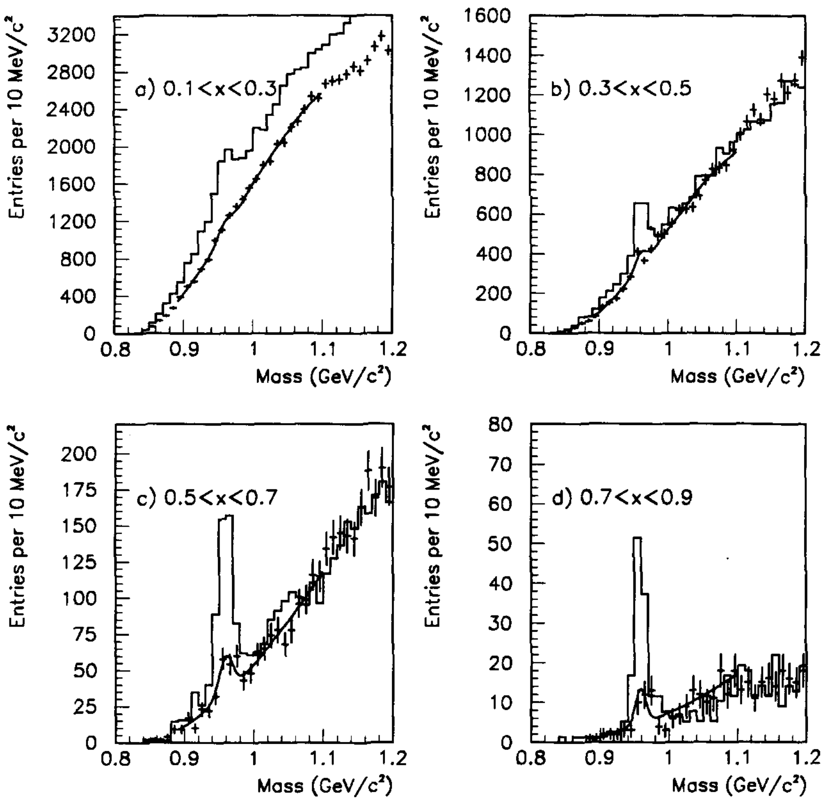


Fig. 3. $\eta\pi^+\pi^-$ mass spectra for different values of $x = E(\eta\pi^+\pi^-)/E_{\mathrm{beam}}$. ALEPH data are shown as points with error bars and corresponding fits. Fully simulated Monte Carlo data (using JETSET 7.3 and normalised to the ALEPH data) are shown as histograms.

description of the background is less good. The level of background arising from photon combinations depends critically on the correct simulation of the $\pi^0$ production rate as a function of energy. Further, since an attempt is made to remove pairs arising from reconstructed $\pi^0$ decays with a tight mass cut, any differences between data and the simulation in the reconstructed $\pi^0$ peak will also lead to different background levels. All these effects have a negligible effect on the $\eta$ signal.

## 4. Measurement of the production of the $\eta'$

The $\eta'$ is identified by the decay $\eta' \to \eta\pi^+\pi^-$. For a given event, all photon pairs with a mass within 100 MeV/$c^2$ of the $\eta$ mass (549 MeV/$c^2$) were taken as possible $\eta$ candidates. For energies lower than about 10 GeV, the $\eta$ mass resolution is dominated by the energy resolution of the ECAL. By constraining the pair mass to be equal to the $\eta$ mass, a better estimate of the 4-momentum of the photon pair from the $\eta$ was made and this improved the mass resolution for the $\eta'$.

Charged pion candidates were selected by considering all charged tracks which have at least 5 coordinates in the TPC, which originate from a cylindri-

Table 2
The corrected $\eta'$ fragmentation function. The errors shown are statistical only while the systematic error on each value (not shown) is about ±23%.

| $x$ range | $(1/\sigma_{total})\,d\sigma/dx$ |
|---|---|
| 0.1–0.3 | $2.6\times10^{-1}\pm0.9\times10^{-1}$ |
| 0.3–0.5 | $5.6\times10^{-2}\pm1.6\times10^{-2}$ |
| 0.5–0.7 | $1.5\times10^{-2}\pm0.5\times10^{-2}$ |
| 0.7–0.9 | $3.4\times10^{-3}\pm1.5\times10^{-3}$ |

cal region of radius 1 cm and half-length 5 cm centred on the nominal interaction point and which have $|\cos\theta| < 0.95$. No attempt at particle identification was made.

The procedure for obtaining the fragmentation function is similar to that used for the $\eta$. The corresponding fragmentation variable is $x = E(\eta\pi^+\pi^-)/E_{beam}$ and the intervals extend from $x = 0.1$ to $x = 0.9$ in steps of $\Delta x = 0.2$. In each interval, the mass spectrum was fitted with a gaussian and a cubic polynomial for the background in the range 0.89 to 1.10 GeV/$c^2$. Since the signal turns out to be small, the mean of the gaussian was constrained to the $\eta'$ mass (958 MeV/$c^2$) and the resolution was taken as the resolution measured for the simulated data in each $x$ range. The $\eta\pi^+\pi^-$ mass distributions from the data and the simulated Monte Carlo, along with the fits corresponding to the data, are shown in fig. 3.

From Monte Carlo, the efficiency is found to rise approximately linearly with $x$ from about 8% to about 39% for large $x$. Most of the loss is accounted for by the efficiency to reconstruct the $\eta$. The fragmentation function is corrected for acceptance losses and the 17% branching ratio for $\eta' \to \eta\pi^+\pi^-$ with $\eta \to \gamma\gamma$ and is shown in fig. 4. While the shape of the JETSET prediction agrees with the data, it is readily seen that JETSET is producing far too many $\eta'$ particles. There is better agreement between HERWIG and the data. The values of the fragmentation function can be found in table 2.

For $x > 0.1$, the data yield $0.068 \pm 0.018$ (stat) $\pm$ 0.016 (syst) $\eta'$ per Z decay, to be compared with the JETSET prediction of 0.27. The ratio of the two is $0.25 \pm 0.06 \pm 0.05$. In the same range, HERWIG gives better agreement, but nevertheless predicts a multiplicity of 0.12 which is still higher than the measurement.

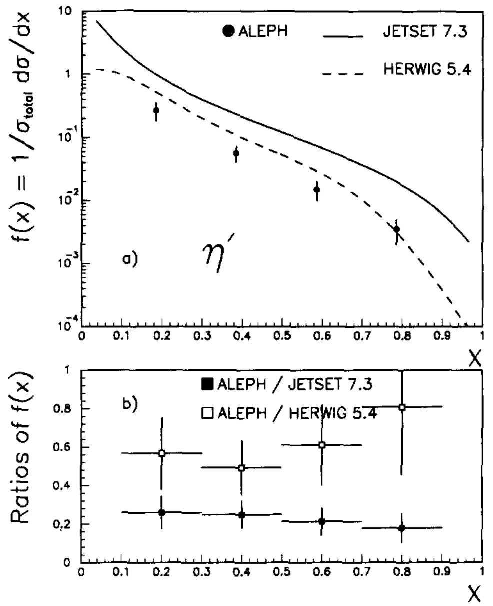


Fig. 4. (a) The corrected $\eta'$ fragmentation function compared with the predictions from JETSET 7.3 and HERWIG 5.4. (b) The ratios of the fragmentation functions. All errors shown are statistical only.

The systematic error is dominated by uncertainties arising from the fitting. This uncertainty was estimated by varying the assumed resolution and fit range and found to be about 22%. Other sources of uncertainty are (a) the efficiency to reconstruct the $\eta$ candidate and (b) to select it with the ±100 MeV/$c^2$ mass cut, and (c) the efficiency to reconstruct a pion pair. Combining these effects in quadrature yields 5% which combined with the fitting error gives a total systematic error of 23%. As can be seen from fig. 3, the background under the $\eta'$ peak is described by the simulation to 20%.

The MARK II Collaboration [1] measured an $\eta'$ multiplicity for $x > 0.2$ of $0.09 \pm 0.03 \pm 0.02$ in hadronic events at $\sqrt{s} = 29$ GeV and compared this to their JETSET 5.2 prediction of 0.14. This corresponds to a ratio of data to JETSET of $0.64 \pm 0.21 \pm 0.14$, which is substantially larger than the measurement reported here, although the two are consistent within the errors.

## 5. Discussion of the results

In considering the measurements of the fragmentation functions, it is important to identify the origins of the $\eta$ and $\eta'$ particles in the hadronic decays of the Z. In the context of the JETSET Monte Carlo, 57% (55%) of $\eta$ particles come from the string and 36% (30%) come from $\eta'$ decays, while 92% (85%) of $\eta'$ particles come from the string (numbers in brackets are for $x > 0.1$).

It is quite clear that the JETSET prediction for the $\eta'$ fragmentation function and hence multiplicity is much higher than the measurements. Experimentally a ratio of $\eta'/\eta$ of $0.23 \pm 0.06 \pm 0.05$ is observed, compared with the JETSET prediction of 0.82. Bowler [7] has pointed out that the choice of mixing angle [12] employed in JETSET for the transformation of the SU(3) states $(\eta_8, \eta_1)$ onto the observed states $(\eta, \eta')$ may not be optimal. In JETSET, the quark descriptions of the $\eta$ system are

$$\eta = \tfrac{1}{2}(u\bar{u} + d\bar{d} - \sqrt{2}s\bar{s}),$$

$$\eta' = \tfrac{1}{2}(u\bar{u} + d\bar{d} + \sqrt{2}s\bar{s}).$$

This choice corresponds to a mixing angle of $-9.7°$, while some experimental results prefer more negative angles around $-20°$ [12,13]. The production rate of pseudoscalar mesons from the string in the JETSET model is solely a function of their quark content, modified only slightly by the availability of phase-space. The model allows for the suppression of the heavier $s$ quarks, but since the amplitudes for the different $q\bar{q}$ pairs are the same in magnitude in the description of the $\eta$ and the $\eta'$, their production rates from the string are essentially the same. Choosing a mixing angle closer to the preferred value of $-20°$ would reduce the $\eta'/\eta$ ratio by a factor of about 1.5.

Since a significant fraction of the $\eta$ rate in JETSET comes from the decays of the $\eta'$, it is slightly surprising that the measured $\eta$ multiplicity is reasonably well described by JETSET. However, reduction of the $\eta'$ rate by a change in the mixing angle would automatically lead to partial compensation by an increase in prompt $\eta$ production and this would be consistent with the measured fragmentation function for the $\eta$ being slightly harder than the prediction.

Although the $\eta'$ rate predicted for the full $x$ range by JETSET is only 0.66 per hadronic decay of the Z, the effect of these particles is not insignificant. In an average hadronic decay of the Z, they account for 3.9 GeV of the energy, and give rise to 1.2 charged pions, carrying half of the $\eta'$ energy, and 2.3 photons. To examine the effect of changing the $\eta'$ rate, JETSET was modified so that 80% of these particles formed from the string were replaced by other hadrons in their usual proportions. This resulted in $\eta'$ and $\eta$ multiplicities for $x > 0.1$ of 0.07 and 0.26 respectively. The average photon multiplicity was found to fall by 1.0 units, with a reduction of the energy carried by photons of 0.6 GeV. This was compensated by the extra energy carried by all other stable particles. The average charged multiplicity was reduced by 0.4 units, while the charged energy hardly changed.

In JETSET, the mass suppression is taken into account by the effective quark masses. However, it is known from the production rates of vector and pseudoscalar mesons that suppression arising from the actual hadron mass must be considered. This is allowed for better in the HERWIG model where the multiplicity is controlled by the volume of phase space available in the decays of colour neutral *clusters* to hadrons compatible with the flavour of these clusters. For $x > 0.1$, HERWIG predicts an $\eta'/\eta$ ratio of 0.28 in good agreement with the measured value.

## 6. Conclusions

The fragmentation functions of the $\eta$ and $\eta'$ have been measured at $\sqrt{s} = 91.2$ GeV. For $x > 0.1$, the multiplicities are $0.298 \pm 0.023$ (stat) $\pm 0.021$ (syst) $\eta$ per Z decay, and $0.068 \pm 0.018$ (stat) $\pm 0.016$ (syst) $\eta'$ per Z decay. The ratio of the measured multiplicity for the $\eta'$ to the prediction from JETSET is $0.25 \pm 0.06 \pm 0.05$. This can be explained qualitatively by the quark description of the mesons employed by JETSET and the limitation of the description of meson masses by effective quark masses. The multiplicity predicted by HERWIG is closer to the measurement but is also significantly larger.

In spite of 65% of all $\eta'$ particles decaying to states containing an $\eta$, it is found that the JETSET Monte Carlo provides a reasonable description for the $\eta$ both in shape and magnitude, although the shape of the data is somewhat harder which is consistent with a greater fraction of prompt production. HERWIG predicts too many $\eta$ particles at low $x$.

While JETSET has been tuned to reproduce global features of the data, the precise $\eta'$ rate can have a significant impact on some physics issues. In particular, the measured strength of the Bose–Einstein effect in $e^+e^-$ annihilations can be understood better with JETSET in the light of the substantial reduction of the predicted $\eta'$ multiplicity, as was demonstrated in reference [6].

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